Evolution of Partial Discharges during Early Tree Propagation in Epoxy Resin

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ABSTRACT

Electrical tree growth is a precursor to dielectric breakdown in high voltage polymeric insulation. Partial discharge (PD) has a close relationship with electrical tree propagation and can be both used to understand the aging process, and as a diagnostic tool for asset management. In this paper it is shown that PD patterns change through the early stages of tree growth, and consideration of these changes gives insight into the processes of tree growth. Here, trees have been grown in epoxy resin in needle-plane geometries with 2 mm gaps, at 15 kV peak AC. The PD phase-resolved pattern can be regarded as a combination of the well-known turtle-like and wing-like PD patterns. As a tree extends its length, a wing-like pattern is seen and the maximum discharge magnitude has an almost linear relationship with the maximum length of the growing branch. Comparison of the energy released by discharges and the vaporization energy needed for tree growth supports the proposal that the wing-like pattern corresponds to PDs responsible for growth in length of the trees. Implications for mechanisms for tree growth are considered. Results suggest that asset managers may be able to use partial discharge analysis to distinguish different stages of tree growth, providing a valuable prognostic tool for optimising high voltage plant management and replacement.

Index Terms — **PD phase resolved pattern, electrical tree, wing-like PD, turtle-like PD, asset management, prognostics.**

1 INTRODUCTION

ELECTRICAL trees are hollow structures which develop prior to electrical breakdown in high voltage polymeric insulation. The occurrence of partial discharges (PDs) is closely related to electrical tree propagation, and PDs are widely considered to be the energy source for tree propagation [1, 2]. Dodd et al found that the rate of damage accumulation in a material was proportional to the electrostatic energy dissipation by partial discharges, and the vaporization energy required to form tree structures was one twentieth to one seventieth of the total energy input from the external circuit [1]. Schurch et al further related released energy to the volume of damage in tree channels using high resolution 3D imaging of tree structures [2].

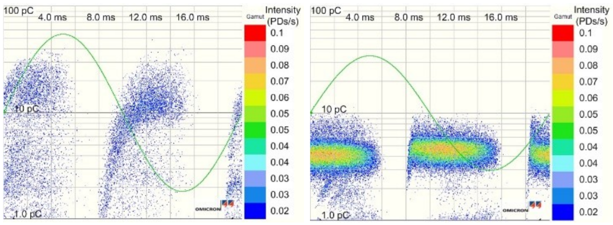
Discharges are typically characterized by their magnitude, number per power cycle, phase-resolved patterns, and dependence on applied voltage [3-5]. Champion and Dodd divided tree growth into three stages by plotting the ratio of (accumulated damage)/(zone radius) against the zone radius: to give an initiation stage, a stable growth stage, and a runaway stage [3]. Our previous study indicated that the whole life of the tree can be divided into five stages: inception, fast forward growth, fine tree growth, development of tree channels, and finally reverse tree growth. Partial discharges have distinguishable characteristics at the different stages of tree growth, and changes in partial discharges were found to correspond to the identified phases of tree propagation [4].

PD analysis is already widely used in commercial asset management to monitor insulation degradation [6-8]. It also offers a non-visual method to evaluate the presence of treeing in opaque samples in the laboratory, such as micro- and nano-filled samples [9]. Generally PD analytics are used to monitor the rate of aging rather than absolute condition.

Suzuoki et al [10, 11] employed artificial defects (long single channels) in polyethylene to characterize changes of PD with tree growth. It was found that the artificial defect size played an important role in determining the phase-resolved PD pattern. In long narrow channels, PD shows a wing-like (or triangular) pattern, which is considered to be typical of a branch tree. In short or wide channels, PD have a turtle-like (or rabbit-like) pattern, which is considered to be typical of voids [10, 11]. Figure 1 illustrates the general form of PD patterns which are described as wing-like and turtle-like; descriptions used extensively here.

Manuscript received on 28 March 2017, in final form28 June 2017, accepted 29 June 2017. Corresponding author: Z. Lv.

DOI: 10.1109/TDEI.2017.006731



(a) Wing-like PD (b) Turtle-like PD

Figure 1. Typical PD patterns observed in electrical trees.

Wu et al proposed a physical model considering PD propagation in long narrow channels [12, 13]. However, the studies using artificial defects were with relatively low voltages and large needle-plane separations, and the PD signal was usually detected before trees propagated from the tip of the artificial defects. As a result, even though these studies give indications of the PD patterns associated with different defects, the results are from a quasi-equilibrium state rather than a dynamic condition.

This paper describes and explains the evolution of PD patterns as trees and branches propagate, especially focusing on early stage growth.

2 EXPERIMENTAL

2.1 SAMPLE PREPARATION

A conventional point-to-plane sample configuration, generating high divergent fields at the needle tip was used. The samples were fabricated using epoxy resin LY/HY 5052. Details of sample fabrication have been described previously [14]. Ogura needles of 1 mm diameter and 3 μm tip radius were used as HV voltage electrodes, with a gap to the planar ground of 1.9 ± 0.1 mm. The plane epoxy surface opposite the needle was coated with aluminum by vacuum evaporation. 10 samples were used for this study. Trees were pre-initiated at 12 kV rms, resulting in trees of about ~50 μm length, hereafter called 'the initial tree'. Trees were pre-initiated to ensure uniform conditions for subsequent testing, and a common point of initial reference.

2.2 EXPERIMENTAL SET-UP AND TEST PROCEDURE

Electrical tree growth was monitored with simultaneous partial discharge measurement using the system shown in Figure 2. The set-up consists of an HV amplifier (Trek; 30 kV peak), a test cell filled with silicone oil, and a monochrome CCD camera fitted with a telecentric lens with a field of view of 6 mm wide by 5 mm high. This lens enabled monitoring of the whole tree length. A wideband (9 kHz to 3 MHz) digital measurement system (MPD 600) was used to acquire PD data in compliance with IEC 60270. A balanced circuit was employed to mitigate background noise and to improve the sensitivity of the measurements. Copper tubes were used as connecting rails to eliminate corona. The sample was at room temperature and immersed in silicone oil to prevent flashover. The sensitivity of the measurement system was ~0.35 pC and a minimum detection setting of 0.4 pC was used to eliminate background noise. This system allows recording of the PD stream during the entire test. The samples were stressed continuously at 15 kV peak (10.6 kV rms) 50Hz. Electrical tree images were captured every 60 seconds during the test. Other details of the set up can be found in [14].

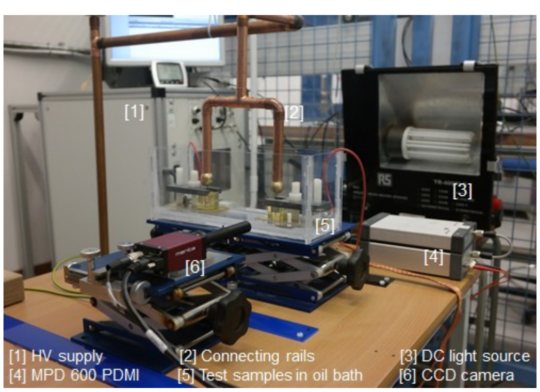


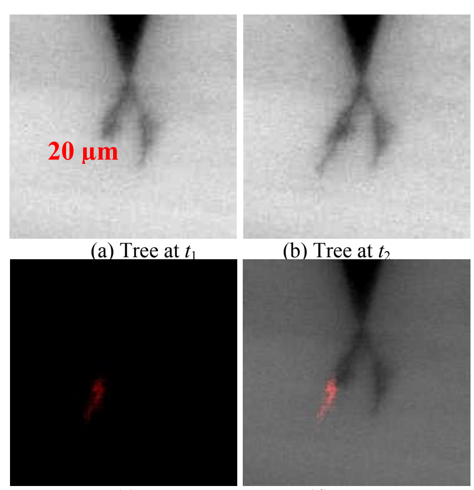
Figure 2. Test equipment and system.

3 RESULTS AND DISCUSSION

3.1 PD EVOLUTION WITH TREE GROWTH

Our previous study showed that the treeing process in epoxy resin under 15 kV peak AC voltage can be divided into five stages [4]. After the initiation (stage 1), dark branches quickly grow and are associated with increasing PD magnitude (stage 2). The tree volume is then extended by the growth of much finer trees during a period with almost no measured PD signal and no extension of the previously formed dark branches (stage 3). When the fine tree approaches the plane electrode, PD is again readily detected and its magnitude increases in time (stage 4). When a tree channel connects the two electrodes (bridges the dielectric), the PD magnitude and intensity increase and the tree develops further dark branches. In particular, one structure, which the authors have termed a 'reverse tree', develops from the planar electrode, growing back through the fine tree structure towards the needle (stage 5). Breakdown then ensues.

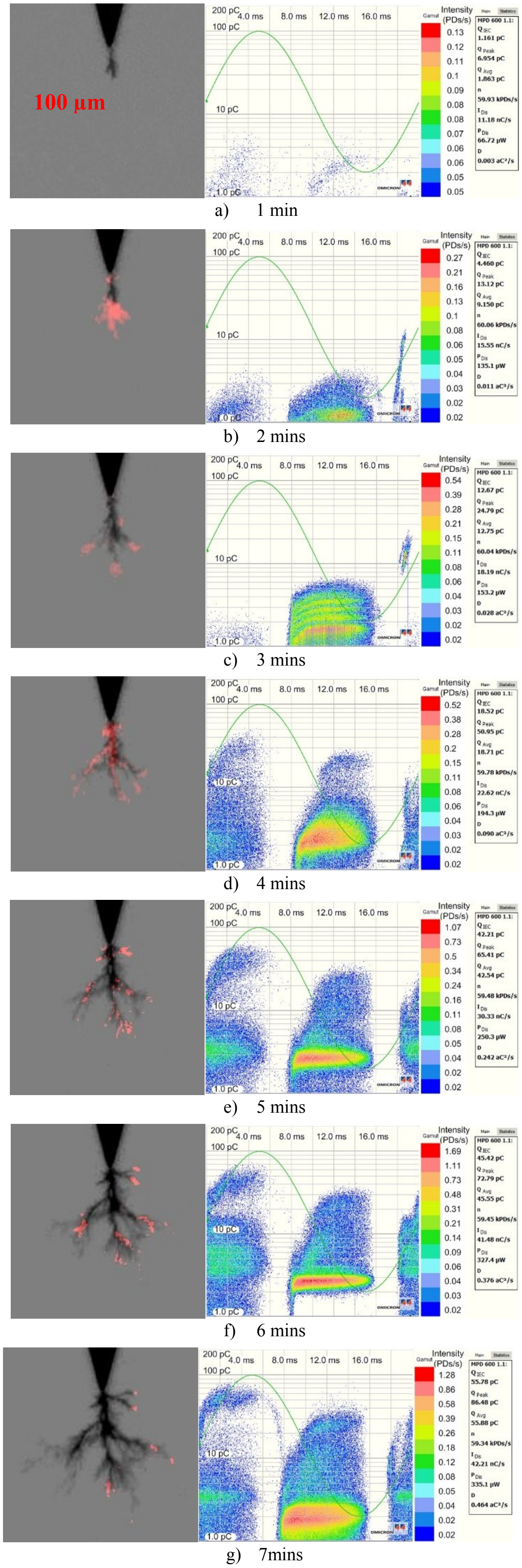
In early stages of development, the visual aspect of a tree is simple and with few branches [4]. The corresponding PD pattern is also relatively straightforward when considering the relationship between tree growth and the PD pattern's evolution. The PDs in stages 4 and 5 are more complex. So firstly the early branch tree and its corresponding PD signal are analyzed.



(a) Tree at t_1 (b) Tree at t_2

(c) t_2-t_1 (d) a+c

Figure 3. The image processing procedure.



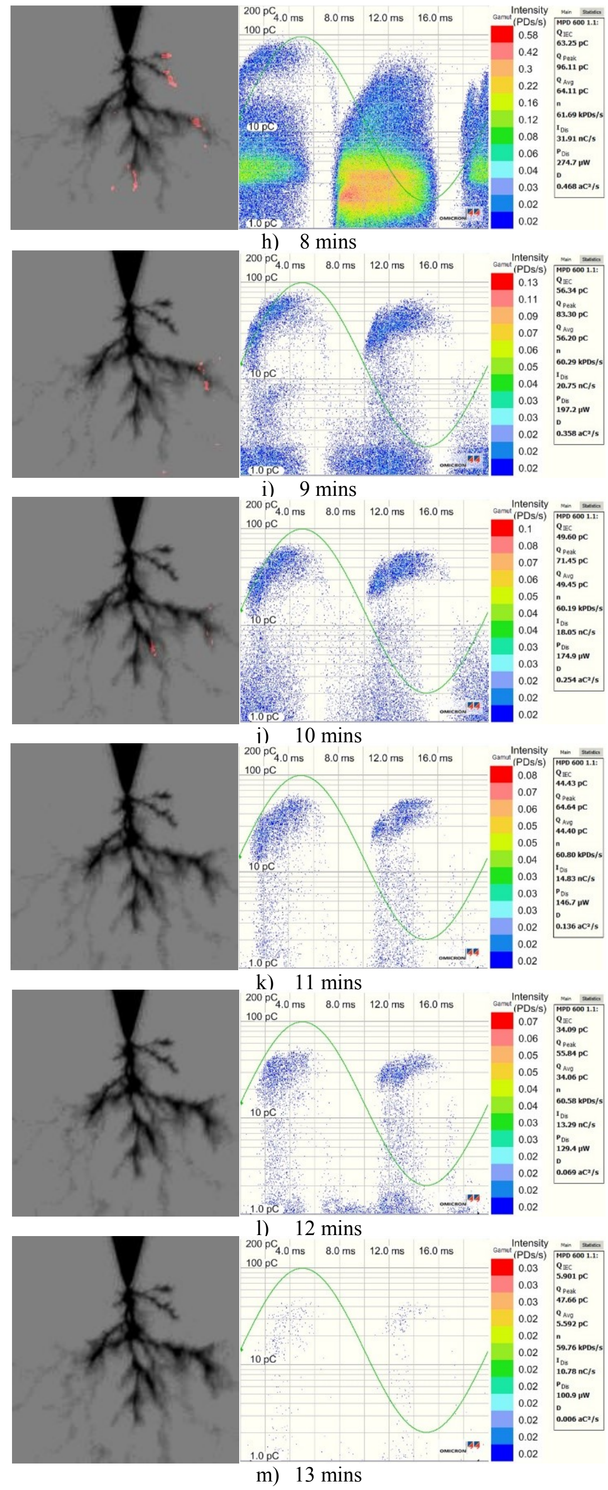


Figure 4. Early branch tree propagation with its corresponding PD phase-resolved pattern. The scale bar in (a) applies to all images.

The tree growth character can be seen by comparing the images at neighboring times. To highlight more clearly the tree growth in each minute, firstly a square area around the needle tip with dimensions of 181×181 is cut from the origin figure with dimensions of 2452×2056, the cut figure is then magnified to better show the early branch tree around the needle tip, as shown in Figures 3a and 3b. The apparent resolution seems to be low, due to the magnification of a very small area which is cut from a high resolution image. Then the newly developed parts of the tree are identified by subtraction between figure 3a and 3b, the two tree images at neighboring time points. The result is plotted in red and shown in figure 3c; then figure 3c is inserted as a semitransparent layer onto the figure 3a, the result is shown in figure 3d. The distribution of newly developed branch and its relative position according to the previous tree structure can be seen in figure 3d. The choice of colors and contrast used here it to try to optimize the image for the reader. Figure 4 shows images from a typical tree taken every minute from 0 to 13 mins, along with the corresponding PD patterns accumulated within that minute. The tree images are all processed by the above procedures. There is a small amount of 'fine tree' growth since the 5th min. The branch tree is much darker than the fine tree. By setting a threshold value higher than the fine trees' image, the highlighting process neglects the growth of fine tree and only focus on newly propagated branch tree.

Figure 4a shows the pre-initiated tree which is a short branch tree about 50 μm long and with branches of 1-2 μm diameter. It corresponds to a low magnitude (maximum value ~5 pC) wing-like PD pattern within the first minute. This is consistent with the study on much larger artificial defects, 2 mm long and 10 μm wide, that showed PD developing into a wing-like pattern when new tree channels initiated [11, 12].

As shown in Figure 4b, during the 2nd minute, the tree rapidly propagates a further 50 um, and is accompanied by new small branches near the needle tip. In this period, there is a new turtle-like PD pattern superimposed on the previous wing-like PD in the negative half cycle; and a new wing-like pattern is seen in the phase range 330-360°. The positive half cycle pattern is unchanged from the 1st minute.

During the 3rd minute the tree continued to grow from localized points on its periphery. The magnitude of turtle-like pattern increases, and is characterized by several values of PD magnitude which occur more frequently over the phase range 160-270°. The magnitude of wing-like PD also increases, and the root part of the wing at 330° disappears. The wing-like pattern in the positive cycle becomes more turtle-like.

During the 4th minute, shown in Figure 4d, the tree growth is relatively fast. One new long branch, seen on the left, quickly propagates to a similar length as the previous longest branch at the center; the previous longest branch at the center propagates further too. There are also two new small branches developing near the electrode tip. The PD patterns in both half cycles have developed turtle-like and wing-like patterns, and the magnitude of the wing-like patterns are similar or a little higher than those of the previous wing-like PD in the range of 330-360°. However in the negative half cycle, it seems that the turtle-like PD still exists at the centre of the wing. The magnitude of the turtle-like PD group is lower than the wing-like PD, but the intensity of the turtle-like part is higher than that of wing-like group.

The tree growth and PD patterns from the 5th to the 8th minutes maintain the same trends. All the tree growth is at tree tips rather than at the needle tip or at the heart of the tree in this period. In the 5th minute distinct wing-like patterns are superimposed on turtle-like patterns in both half cycles. The whole PD pattern can be regarded as a combination of several turtle-like and wing-like components. For example, the PD pattern in the negative half cycle during the 7th minute can be divided into at least 3 parts: higher magnitude wing-like PD (maximum: ~40 pC); lower magnitude wing-like PD (maximum: ~20 pC); and smaller turtle-like PD (between 1-3 pC). With the growth of the tree, the maximum magnitude of wing-like PD has increased from 50 pC in the 4th minute to 96 pC in the 8th minute. The maximum magnitude in the positive half cycle is higher than that in the negative half cycle.

During the 9th and 10th minutes, most of the tree branches stop growing, and only two long branches in the right of the images grow slowly. During the same period, the PDs that make up the main turtle-like pattern and the lower magnitude wing-like pattern are no longer present. The high magnitude wing-like PD now dominate the measurements, and the phase plot's shape corresponds to the sinusoidal voltage value. The maximum magnitude and the repetition rate of the wing-like pattern is reducing in this period. During the 11th, 12th and 13th minutes, the maximum magnitude of the wing-like PD decreases to lower than 70 pC and then, in a period where there is almost no new branch tree growth, the PD activity gradually all but stops.

The PD characteristics of magnitude, intensity and phase-resolved pattern all change with the tree structure and growth. Former studies typically use the tree length to characterize the tree growth rate [3-5, 15]. Here, the area of the highlighted parts of the images can give a sense of tree growth from another perspective. It is useful to call those branches with newly-grown parts in each minute 'actively-growing branches'. During the first eight minutes, the PD magnitude and intensity increase with tree extension. Between the 9th and 13th minutes, the PD magnitude and intensity decrease as tree extension slows. The extinction of PD follows, with the cessation of growth of the tree in the 13th minute.

It is noted that as long as there is a growth of the branch-tree, there is PD. However, we note that we are ignoring the fine tree propagation. As our previous study shows, fine-tree propagation does not contribute to detectable PD, presumably because any corresponding PD signal is lower than the system resolution. However, measured PD does not always result in observed tree propagation (c.f. the 11th, 12th and 13th minutes). It seems that not all the partial discharge contributes to visible branch-tree growth.

It can be seen that both turtle-like and wing-like PD patterns are found in our results. Turtle-like PD patterns are reported to be from voids or short channels [12]. It is considered that in a short channel, the PDs can readily propagate from one side of the void to the other, so all the PDs have almost the same value (limited by void size), and so the PD pattern has a uniform magnitude and forms a turtle-like pattern. Wing-like PD is reported to be typical of tree-like structures or long narrow channels, because not all the PDs can propagate to the end of the channel. In this case, higher point-on-wave voltages result in physically longer and higher magnitude PD [12].

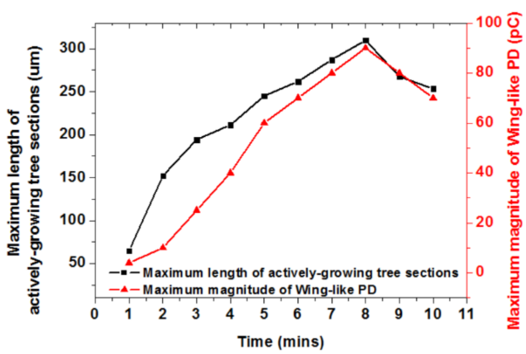
The turtle-like PD pattern and wing-like PD pattern are now discussed separately.

3.2 THE WING-LIKE PD PATTERN

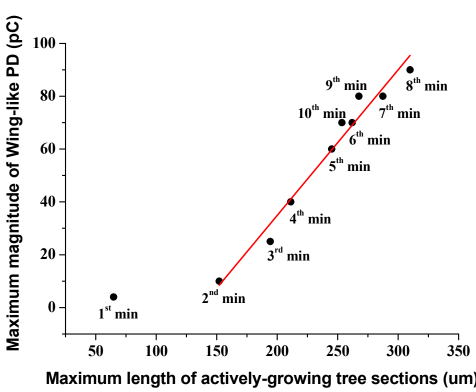
3.2.1 PD MAGNITUDE AND TREE LENGTH

The preceding discussion has shown that the PD magnitude and pattern have a close relationship with the growth of the early stages of the branch tree. From Figure 4, it can be seen that the maximum magnitudes are normally associated with wing-like PD groups. However, that is not true for all the periods, as sometimes the wing-like PDs may disappear for a while and just leave the turtle-like PD. It can also be seen that the magnitude of turtle-like PD shows no relationship with the growth of the branch-tree, and the magnitude of wing-like PD shows a strong correlation with tree growth. The maximum length of actively-growing tree sections is calculated according from the images shown in Figure 4, by counting and calculating the pixel distances between the needle tip and tip of actively-growing tree sections.

Figure 5 shows the relationship between maximum length of actively-growing tree segments, and the maximum magnitude of PD, which in this case are in the wing-like cluster. The tree length only includes 'actively-growing' branches with new growth within that minute. In the 9th and



(a) time dependence of the two parameters



(b) linear fitting between the two parameters

Figure 5. The relationship between maximum length of actively-growing tree sections and maximum magnitude of wing-like PD.

10th minutes, the longest tree channel does not grow, so the value is lower, because growth is only in shorter tree branches. Figure 5b shows the linear fit between the 2nd and 10th mins, it can be seen that the maximum PD magnitude shows almost linear relationship with the maximum length of actively-growing tree segments between the range of 150-350 µm. This relationship is much stronger than the previous reported average PD magnitude with maximum tree length [5].

It is considered that wing-like PD groups with different magnitudes correspond to PDs in channels with different lengths: higher magnitudes corresponding to longer channels. When PDs occur in channels with similar lengths, they may form one clearly defined area, as in the 10th minute shown in Figure 4j. When the PDs occur in channels with various lengths, they may form a number of wings with different magnitudes. When activity occurs in tree channels with a wide range of lengths, the patterns may merge resulting in a triangle-like shape, as shown in the 5th to 8th minutes.

As the maximum PD magnitude corresponds to activity over the maximum active length, it is implied that lower magnitude PDs within the same wing-like pattern (under lower point-on-wave voltage) are associated with discharges which do not propagate to the end of the tree. In this case a PD may not cause damage at the tree tip. We can suggest that only those PDs that can propagate to the tree tips will cause branch extension. It is possible that the lower magnitude PDs do contribute to widening of existing tree channels, however, limitations of optical imaging prevent confirmation of this supposition. More advanced techniques such as 3D XCT imaging or SEM are needed to provide better resolution of the tree channel [16, 17].

In the experiments reported here, the maximum magnitude of the wing-like PDs in the 8th, 9th and 10th minute are 96.1, 83.3 and 71.5 pC respectively. The maximum PD magnitude tends to decrease after the 8th minute and at the same time the longest branch stops growing. The 71.5 and 83.3 pC PDs do not have sufficient magnitude to cause new damage on the longest tree channel tips as shown in figure 4h. However they are large enough to traverse the whole length of some of the shorter branches, and so cause new damage on the tree tips of some shorter tree channels as shown in Figures 4i and 4j. From 11 minutes onwards, the maximum PD magnitude decreases to lower than 70 pC, and then no significant extension to the tree length can be observed. PDs are still active in this period, but fail to extend the tree being observed. It should be noted that the growth of the fine filamentary trees which are not associated with measurable discharges are not included in this analysis.

3.2.2 ENERGY OF WING-LIKE PD

The reason that the PD energy efficiency previously calculated is only between 5% and 14% [1, 2] may be that only the PDs that can reach the tree tips can result in tree growth. Segregation of the energy of only those PD associated with the maximum magnitude in a wing-like pattern, is difficult if the wings are not distinct from each other. It is therefore generally difficult to evaluate the relationship between the energy released by the PDs which can reach the tree tips and the tree growth. However, our experimental results show key features during the 2nd and 3rd minutes. As new tree branches develop, wing-like (or Rabbit-ear) PD patterns are seen between 310 and 360°, as shown in Figures 4b and 4c. To illustrate the dynamic characteristics more clearly, figure 6 and Figure 7 show 10 s accumulated PD patterns during the 2nd and 3rd minutes. It can be seen that this wing-like group occurs only within a small phase range around 330°, while its magnitude continuously increases with time. One feature is that the wing-like pattern at the phase range between 310°-360° after 1 min 30 s does not contain small values, as shown in Figure 6d. Hereafter, this kind of PD pattern is called an 'exclusively high value wing-like' PD pattern. This means that during the 2nd and 3rd minutes, all the PDs in this exclusively high value wing-like pattern seem to be able to extend to the tree tip. Figure 8 shows five cycles of PD pulses at 150 s. In each cycle, there is only one PD event recorded around 330°, the phase range of exclusively high value wing-like PD. Between 150-270°, there are many PDs contributing to the turtle-like pattern. And between 0-150°, there are almost no PD signals. This combination of PD is only found at the very early tree propagation stage, when new branches start to grow from the pre-initiated branch. This kind of "exclusively high value wing-like" PD pattern may result because: 1) The short length of the newly propagate channel means all the PD are between the needle tip and the tree tip instead of within the newly propagate channel, so there are no lower level values; or 2) The phase of the no-root wing-like PD corresponds to a single point-on-wave when the electric field of the pre-initiated branch tip is high enough to cause PD in the newly developed branch.

It has been estimated that the energy of vaporization per unit volume, E_0, for epoxy resin is 7.56×10^{10} J m^{-3} [1, 2]. The authors' previous work on three-dimensional imaging of tree structures shows that the mean diameter of the early branch

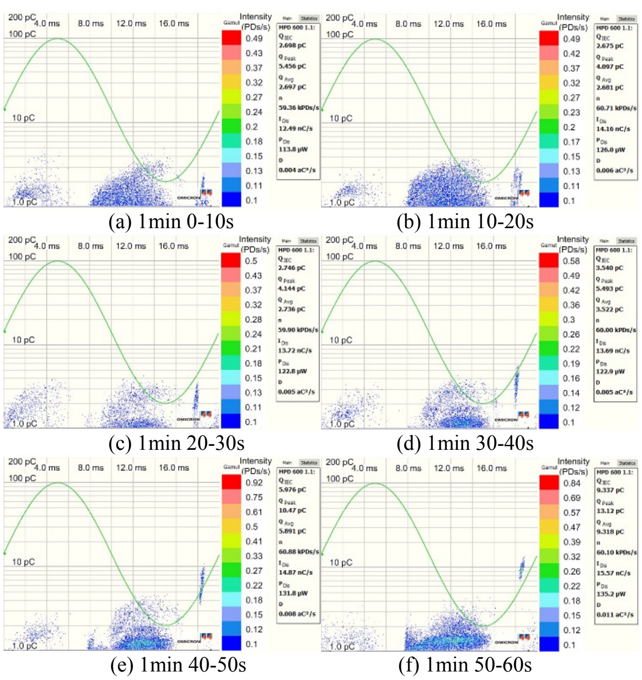

(a) 1min 0-10s (b) 1min 10-20s
(c) 1min 20-30s (d) 1min 30-40s
(e) 1min 40-50s (f) 1min 50-60s

Figure 6. 10 second accumulated PD patterns from the 2nd minute.

tree is 1.9 μm [16, 17]. Here the tree radius is set to be 1 μm as the new branches in the 2nd and 3rd minutes are in the very early stage. By comparing the grey value of the 3rd and 1st images, the number of pixels (n) corresponding to the newly propagate branch is 647. The pixel length l_0 is 2.817 μm and each pixel can be regarded as corresponding to a cylindrical tree channel with a radius of 1 μm and a length of 2.817 μm. So the total energy associated with vaporization of the newly formed branch volume can be calculated as:

$$E = E_0 \cdot n \cdot l_0 \cdot \pi \cdot r^2 \qquad (1)$$

and is thus about 4.3×10^{-4} J.

The total energy released by PD, E_{pd} , within the 2nd and 3rd minutes can be calculated with the following:

$$E_{pd} = \sum_i q_i \cdot v_i \qquad (2)$$

where, q_i is the magnitude of the i^{th} PD, and v_i is the point-on-wave voltage when the i^{th} PD occurs.

The PDs in the wing-like pattern can be segregated by checking whether the PD is in the phase between 310-360°, so that the energy release by the wing-like energy can be calculated. Results show that the total PD released energy within the two minutes is 4.5×10^{-3} J, while the energy released only by the wing-like PD is 3.6×10^{-4} J. It can be seen that total PD released energy is more than 10 times higher than the required vaporization energy, which is consistent with previous analyses [1, 2]. The energy released by the no-root wing-like PDs is only a little lower than the required

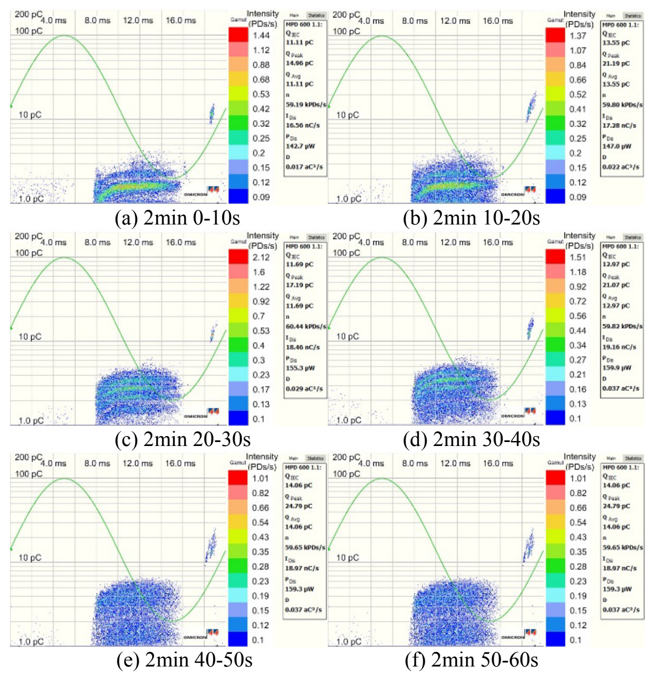

(a) 2min 0-10s (b) 2min 10-20s
(c) 2min 20-30s (d) 2min 30-40s
(e) 2min 40-50s (f) 2min 50-60s

Figure 7. 10s accumulated PD patterns from the 3rd minute.

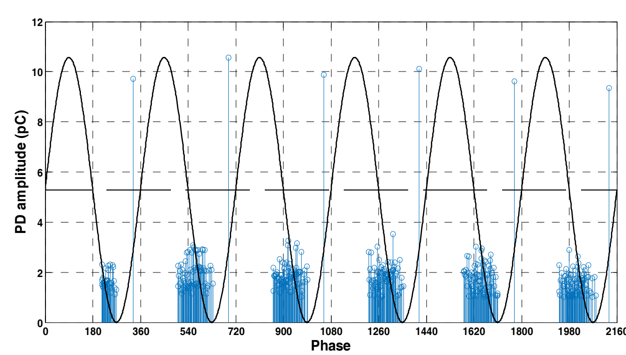


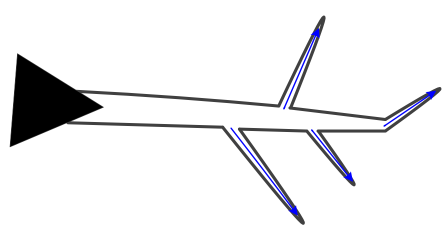
Figure 8. PD pulse sequence for 5 cycles between 150s and 150.1s.

vaporization energy. Even though the calculation of the newly propagate tree volume is approximate, the result supports the hypothesis that not all the PDs provide energy for the tree extension, and only those which can reach the tree tips can contribute to the energy needed for further length growth. No-root wing-like PD clusters also appear at later times, but with more branches having been generated, any individual no-root wing-like pattern is usually obscured by other groups.

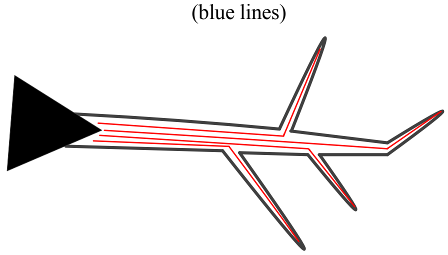
3.3 TURTLE-LIKE PD PATTERNS

The turtle-like pattern is considered to arise from PD in short channels where they propagate from one end to the other, resulting in similar magnitudes even at different instantaneous voltage values [12]. From Figure 4, it can be seen that the maximum magnitude of most PDs in such a cluster is lower than 6 pC. For example, the wing-like PD in the 1st minute in the 65 µm pre-initiated tree is about 6 pC. If the relationship between the maximum magnitude of turtle-like PD clusters and tree length is the same as the wing-like PD, then the PDs in a turtle-like pattern may only propagate in a length less than 100 µm. This limited length of discharge propagation could either eminate from the needle tip, or from a short branch which is not adjacent to needle. In the latter condition, it might be considered that the main branch needs to be relatively conductive, so that the PD occurs only in the specific branch rather than the main branch [18]. Both conditions can generate turtle-like PD due to a limited discharge distance.

From the 10 second PD patterns shown in Figure 6, it can be seen that before 1 min 20s, the PD in the phase range of 150-270° forms a triangle-like pattern. After 1 min 20s, a new turtle-like pattern develops between 310 and 360° increasing in magnitude and losing its root. Between 1 min 30 s and 3 mins, the magnitude of the turtle-like pattern increases along with the magnitude of the wing-like PD, but is always the smaller of the two. After 2 min 10 s, several levels of turtle-like PDs are evident, and their magnitudes continuously increase. It seems that there are three or four levels with magnitudes lower than 6 pC at 2 min 40 s. At the 4th minute (Figure 4), the tree is not growing in length, but the main tree channels are getting wider. With this tree structure change, the turtle-like PD in the phase range of 150-270° becomes triangle-like with another wing-like group above. The low magnitude turtle-like PD pattern in the range of -30° to 90° turns into a triangle-like PD with maximum magnitude of about 50 pC. This value is higher than the previous wing-like PD.



(a) PDs associated with turtle-like patterns occur within branches (blue lines)



(b) PDs associated with wing-like PDs travel the length of the tree (red lines)

Figure 9. Sketch of discharging route of partial discharges.

Several points require further discussion: Firstly, it is hard to explain the several distinct levels of turtle-like pattern if events originate from the needle tip. At the 3rd minute, three new branches are propagating from the same main channel (the pre-initiated tree channel) but at different locations. If the turtle-like PD cluster corresponds to PD from the needle tip to these branch junctions at different distances, this gives an explanation of why distinct levels of turtle-like PDs are seen together. This would be consistent with the previous result that PD magnitude increases linearly with the distance of its propagation. But it cannot explain why the magnitudes of different turtle-like PDs increase with the growth of new branches, as the position of branch junctions won't change with tree growth. In addition, there is no new growth at the needle tip at the 3rd minute when the turtle-like PD markedly increases in magnitude. So the multiple levels of turtle-like PDs cannot result from discharges in new branches from the needle tip. A better explanation is that some of the PDs contributing to the turtle-pattern may not originate from the needle tip, but emanate from the branch junctions towards the branch tips, as shown in figure 9a. As the PDs propagate different distances (branch lengths) in different branches, the turtle-like PDs show multiple-levels with different magnitudes.

Secondly, based on the discussion above, the understanding of the PD pattern between the 2nd and 3rd mins can be more explicit. The multi levels of turtle-like patterns arise from PD between the branch junctions and tree tip. In this case, the main branch between the needle tip and the branch junction is expected to be relatively conductive, otherwise PD should be from the needle tip. The turtle-like PDs only exits between 150-270°. This kind of polarity dependence may be due to the availability of initial free electrons without which a discharge cannot initiate: electrons being readily available from the needle in the negative half cycle. The turtle-like PD between 150-270° would cause significant electron accumulation at or near the tree tip. The no-root wing-like PD around 330° should then be incepted from the tree tip and propagate back to the needle tip, as shown in Figure 9b. As the tree tip has both the highest electric field and availability of free electron at that phase angle, it seems that this high magnitude PD releases so much space charge that almost no PD can be incepted at the positive half cycle.

For most of the period examined, the PD pattern from the positive half cycles and negative half cycles are almost the same. The appearance of the strongly asymmetric pattern between the 2nd and 3rd mins suggests the branches between the needle tip and branch junction are relatively conductive. At the 4th minute, the positive half cycle starts to develop triangle-like or wing-like PDs again. This is due to new non-conductive branches propagating from the needle tip, which can be seen from Figure 4d.

4 CONCLUSIONS

A detailed study of PD evolution with the early tree propagation has been presented, in time frames down to 10 seconds. Several conclusions result:

1. The PD pattern changes during tree growth, and most of the PD in tree channels can be regarded as belonging to one of, or a combination of turtle-like and wing-like PD patterns
2. The wing-like PD pattern corresponds to partial discharges in long channels, and the maximum magnitude of wing-like PD patterns grows linearly with the maximum length of active tree channel over the range 0.15 to 0.35 mm;
3. Analysis of the magnitude and energy of wing-like PDs suggests that the largest PDs in the wing-like pattern can reach the tree tips and are responsible for increasing the branch tree length. PDs with lower magnitude cannot reach the tree tips and the energy generated does not contribute to growth in tree length, but may contribute to widening of the tree channel.
4. The turtle-like patterns may be generated from PD initiated at the junctions between the existing and new tree branches.

Providing diagnostics of tree growth through partial discharge analysis may enable asset managers to use online measurements to distinguish PD associated with tree extension from other activity, which may provide a valuable prognostic tool for optimizing high voltage plant management and replacement. In particular identifying the difference between PDs associated with tree growth and benign activity within a tree may allow fewer unnecessary plant replacement actions, and reduce operational costs.

ACKNOWLEDGMENT

The authors are grateful to the EPSRC for support of this work through the project 'Composite Dielectric Structures with Enhanced Lifetimes' EP/M016234/1, and also 'System Architecture Challenges: Supergen+ for HubNet' EP/M015025/1.

This paper contains data which is openly available from www.manchestertrees.com.

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